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Models for droplet heating and evaporation: an application to biodiesel, Diesel and gasoline fuels

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Abstract: This paper presents our recent progress in the modelling of automotive fuel droplet heating and evaporation processes in conditions close to those in direct-injection internal-combustion engines. Three types of automotive-fuels are considered: biodiesel, Diesel and gasoline fuels. Modelling of biodiesel fuel droplets is based on the application of the Discrete Component (DC) model. A distinctive feature of this model is that it is based on the analytical solutions to the transient heat conduction and species diffusion equations in the liquid phase, taking into account the effects of recirculation. The application of the DC model to fossil fuels (containing potentially hundreds of components), however, is computationally expensive. The modelling of these fuels is based on the recently introduced Multi-Dimensional Quasi-Discrete (MDQD) model. This model replaces a large number of components in Diesel and gasoline fuels with a much smaller number of quasi-components/components without losing the main features of the original DC model. The MDQD model is shown to accurately predict droplet temperatures and evaporation times and to be much more computationally efficient than the DC model. The main features of these models and their applications to three types of automotive fuel droplets are summarised and discussed.

Keywords: Automotive fuel; Biodiesel; Diesel; Droplet; Evaporation; Gasoline; Heating; Multi-component.

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1 Introduction

Studies on the heating and evaporation processes of automotive fuel droplets are crucial to the design of internal combustion engines and ensuring their good performance (1; 2; 3). Previous studies on these processes have been either based on the analysis of individual components, the Discrete Component (DC) model (4; 5; 6), or on the probabilistic analysis of a large number of components (the continuous thermodynamics (7; 8; 9) and the distillation curve (10; 11; 12) models). In the first approach, the DC model is generally applicable to cases when relatively small numbers of components need to be taken into account. In the second approach a number of additional simplifying assumptions have been used, including the assumption that species inside droplets mix infinitely quickly (Infinite Diffusivity (ID) model). In addition, the temperature gradients inside droplets have been ignored in most cases by assuming that the liquid thermal conductivity is infinitely large (Infinite Thermal Conductivity (ITC) model). On many occasions multi-component automotive fuels have been approximated by single components, using the Single Component (SC) model (e.g. n-dodecane has been used to represent Diesel fuel (13; 14; 15) and iso-octane has been used to represent gasoline fuel (16; 17)). Also, recirculation due to relative droplet and gas velocities has been ignored in many cases.

A version of the DC model based on the analytical solutions to the heat transfer and species diffusion equations has been considered in (18; 19; 20; 21; 22). Direct applications of this model have been limited to the case when the number of components in fuels is relatively small (e.g. biodiesel fuels). In the case of fossil fuels (containing potentially hundreds of components), however, the DC model is computationally very expensive when directly applied to modelling droplet heating and evaporation. In response to this problem, the Multi-Dimensional Quasi-Discrete (MDQD) model has been developed (23). In this model, a large number of components in realistic automotive fuels is replaced with a small number of quasi-components/components, taking into account the same effects as considered in the DC model. This model has been shown to accurately predict the temperature of droplets and their evaporation times and to be computationally efficient (see (23; 24; 25; 26)).

In this paper the above-mentioned models are briefly described and some results of their application to automotive fuel droplets in typical engine-like conditions are summarised. Descriptions of the models and input parameters are presented in Section 2. In Section 3, the results of the application of the DC model to the analysis of heating and evaporation of biodiesel fuel droplets are described. Section 4 focuses on the application of the MDQD model to commercial Diesel fuel droplets. Section 5 presents the application of the MDQD model to typical FACE (Fuel used in Advanced Combustion Engines) gasoline fuel droplets. The main results of the paper are summarised in Section 6.

2 Models and input parameters

As in (18; 19; 21; 27; 24; 20; 25), the analyses are based on the assumption that droplets are spherically symmetric, and temperature gradients, species diffusions and the effect of internal recirculation due to relative velocity between ambient gas and droplets are all accounted for using the Effective Thermal Conductivity and Effective Diffusivity (ETC/ED) models. Additionally, the liquid diffusion coefficients for all species are assumed to be the same. The analytical solutions to the heat transfer and species diffusion equations are used in the analysis. The model based on the above-mentioned assumptions is referred to as the Discrete Component (DC) model. This model will be applied to the analysis of biodiesel fuel droplets.

As mentioned in Section 1, Diesel and gasoline fuel droplets can include large numbers of components (up to one hundred and sometimes more), which fall into several groups according to their molecular structure. In this case, application of the DC model to such droplets is

computationally expensive. As an alternative to the DC model, the MDQD model has been applied for the analyses of heating and evaporation of Diesel and gasoline fuel droplets. In the MDQD model, the components with close carbon numbers within each individual group are merged together to form quasi-components. For each group m the values of the average carbon number of quasi-components, \bar{n}_{jm} , have been introduced as (23; 24; 25; 26):

$$\left. \begin{aligned} \bar{n}_{1m} &= \frac{\sum_{n=n_{1m}}^{n=n(\varphi_m+1)} (nX_{nm})}{\sum_{n=n_{1m}}^{n=n(\varphi_m+1)} X_{nm}}, \\ \bar{n}_{2m} &= \frac{\sum_{n=n(\varphi_m+2)}^{n=n(2\varphi_m+2)} (nX_{nm})}{\sum_{n=n(\varphi_m+2)}^{n=n(2\varphi_m+2)} X_{nm}}, \\ \bar{n}_{3m} &= \frac{\sum_{n=n(2\varphi_m+3)}^{n=n(3\varphi_m+3)} (nX_{nm})}{\sum_{n=n(2\varphi_m+3)}^{n=n(3\varphi_m+3)} X_{nm}}, \\ &\dots\dots\dots \\ \bar{n}_{\ell m} &= \frac{\sum_{n=n((\ell-1)\varphi_m+\ell)}^{n=n_{k_m}} (nX_{nm})}{\sum_{n=n((\ell-1)\varphi_m+\ell)}^{n=n_{k_m}} X_{nm}}, \end{aligned} \right\} \quad (1)$$

where $n_{1m}=n_{m(\min)}$ is the minimal value of n for which $X_{nm} \neq 0$, $n_{k_m}=n_{m(\max)}$ is the maximal value of n for which $X_{nm} \neq 0$ (see Table 3 for gasoline fuel droplets), $\ell = \text{integer}((k_m + \varphi_m)/(\varphi_m + 1))$. Parameter φ_m is assumed to be integer; $\varphi_m + 1$ is equal to the number of components to be included in quasi-components, except possibly the last one in the group. φ_m is assumed to be the same for all quasi-components within group m . If $\varphi_m = 0$ then $\ell = k_m$ and the number of quasi-components is equal to the number of actual components (in this case the MDQD model reduces to the DC model). φ_m and k_m depend on m in the general case.

This approach to generation of quasi-components is based on the selection of a number of components within each group forming a quasi-component ($\varphi_m + 1$). The number of components within each quasi-component, except possibly the last one, (n_c) is taken equal to the nearest integer of the ratio k_m/n_q , where $n_q = \ell$ is the number of quasi-components. If k_m/n_q is not an integer then the number of components in the last quasi-component (n_{lc}) is either greater than n_c , if $(k_m/n_q) > n_c$, or less than n_c , if $(k_m/n_q) \leq n_c$. The molar fractions of these quasi-components/components are estimated as (23):

$$\left. \begin{aligned} X_{1m} &= \sum_{n=n_{1m}}^{n=n(\varphi_m+1)} X_{nm}, \\ X_{2m} &= \sum_{n=n(\varphi_m+2)}^{n=n(2\varphi_m+2)} X_{nm}, \\ &\dots\dots\dots \\ X_{\ell m} &= \sum_{n=n((\ell-1)\varphi_m+\ell)}^{n=n_{k_m}} X_{nm}. \end{aligned} \right\} \quad (2)$$

The results predicted by the following models will be compared in our analysis:

1. the contributions of all components are taken into account using the DC and ETC/ED models (indicated as (ME));
2. the contributions of all components are taken into account using the ITC/ID model (indicated as (MI)); and
3. a combination of the ITC and SC models, in which the fuel is approximated by individual components (iso-octane, for gasoline fuel (indicated as (IO)), n-dodecane, for Diesel fuel (indicated as (ND)), and the dominant components (by molar fractions) for biodiesel fuels (indicated as (SI))).

Note that the predictions of the ITC/ID model have been inferred from the same numerical code as used for the ETC/ED model but with substantially increased values of liquid thermal conductivities and species diffusivities; both were increased by a factor of 100.

The discrepancies between the evaporation times predicted by all models in comparison to the ME model will be estimated as:

$$\text{Error} = \left| \frac{t_{ME} - t_{\text{model}}}{t_{ME}} \right| \times 100\%. \quad (3)$$

Similarly, the errors in the estimation of droplet surface temperatures are calculated using the same Formula (3) with t replaced by temperature T .

The droplets, with radii and temperatures at the initial stage of evaporation of $R_d = 12 \mu\text{m}$ and $T_{d0} = 300 \text{ K}$, respectively, are assumed to be moving in still air at $U_d = 10 \text{ m/s}$. In the case of biodiesel and Diesel fuel droplets, ambient air pressure and temperature are assumed equal to $p_g = 32 \text{ bar}$ and $T_g = 700 \text{ K}$, respectively. In the case of gasoline fuel droplets, ambient air pressure and temperature are assumed equal to $p_g = 5 \text{ bar}$ and $T_g = 550 \text{ K}$, respectively. These conditions are based on the previously reported data (19; 20; 21; 23; 26; 27; 28; 29; 30; 31).

3 Biodiesel fuel droplets

The analysis presented in this section is focused on the modelling of biodiesel fuel droplet heating and evaporation. The temperature gradients and species diffusions inside the droplet are taken into account based on the analytical solutions to heat transfer and species diffusion equations, which are incorporated into a numerical algorithm (see (22; 19)). Unlike typical fossil fuels, such as gasoline and Diesel fuels, which can potentially be composed of hundreds of components, biodiesel fuel is composed of a relatively small number (up to 16) of fatty acid methyl esters (32; 33; 34; 35). This allows us to analyse species diffusion inside droplets based on the Discrete Component (DC) model, in which the diffusion of species is described without any additional approximations.

The analyses and results of the modelling of biodiesel fuel droplet heating and evaporation, using the above-mentioned approach, were presented in (20; 19; 21). In the current paper, an analysis similar to the one presented in (19) is performed but for three of the most widely used types of biodiesel fuels: soybean methyl ester (SME), rapeseed methyl ester (RME) and palm kernel methyl ester (PMK), the compositions of which are described in (20; 21), and using the engine conditions and parameters described in Section 2. The thermodynamic and transport properties of methyl esters are inferred from (21; 19).

The plots of the droplet surface temperatures (T_s) and radii (R_d) versus time, for these three types of biodiesel fuels, are presented in Figs. 1–3. The general trends of the curves shown in these figures are the same as presented in the previous case studies (see (22; 20; 21; 19)), but the errors in droplet surface temperatures and evaporation times, predicted by the MI and SI models relative to those predicted by the ME model, were different from those described in our previous papers. The maximal errors for these surface temperatures and evaporation times for the results predicted by the MI and SI models relative to those predicted by the ME model are shown in Table 1.

As one can see from Table 1, the maximal errors in evaporation times predicted by the MI model are those for RME. These errors predicted by the SI model are maximal for PMK. In all cases the MI model gives more accurate results compared with the SI model and the evaporation times predicted by the MI and SI models are shorter than those predicted by the ME model. The maximal errors in predicted droplet surface temperatures are about the same for all models and all three biodiesel fuels and lie in the range 7.3% – 8.4%.

Table 1 The maximal errors of surface temperatures and evaporation times, predicted by the MI and SI models relative to those predicted by the ME model for SME, RME and PMK biodiesel fuels; these errors have been estimated based on Expression (3).

Biodiesel	$T(\text{MI})$	$T(\text{SI})$	$t_{\text{evap}}(\text{MI})$	$t_{\text{evap}}(\text{SI})$
SME	7.9	7.9	1.1	1.2
RME	8.4	8.4	14.6	15.9
PMK	7.3	7.4	2.7	26.9

These discrepancies between the predictions of droplet surface temperatures and radii can be related to the fact that at the final stage of droplet evaporation the mass fractions of species with larger numbers of carbon atoms n (e.g. C24:1 M and C22:1 M) increase at the expense of species with smaller n (e.g. C16:0 M). At time instants close to the complete evaporation of droplets, mass fractions of all species except the heaviest component (C24:1 M) decrease with time. This is illustrated in Fig. 4, where the time evolutions of surface mass fractions of four dominant species are presented. The species with larger n tend to be less volatile and have higher wet bulb temperatures than the species with lower n . The results shown in Fig. 4 are consistent with those shown in Fig. 5, where the mass fractions of species as functions of the normalised distance from the centre of the droplet are shown. Plots similar to those shown in Fig. 5 but for droplet temperatures are shown in Fig. 6. Figs. 5 and 6 clearly show the limitations of the ITC and ID models widely used for the modelling of droplet heating and evaporation.

4 Diesel fuel droplets

As explained in Section 3, the main difficulty with modelling Diesel fuel droplet heating and evaporation, compared with biodiesel fuel droplets, lies in the fact that Diesel fuels contain many more (potentially over 100) components, compared with biodiesel fuels (up to 16 components). As mentioned earlier, the modelling of Diesel fuel droplet heating and evaporation have been mainly based on the probabilistic analysis of a large number of components (e.g. the continuous thermodynamics or distillation curve models) and rely on a rather crude assumption that species inside droplets mix instantaneously. The application of the DC model to the modelling of Diesel fuel droplets has been seen as a rather computationally expensive approach for practical engineering applications.

An alternative approach for taking into account the full composition of Diesel fuel when modelling this fuel droplet heating and evaporation was introduced in (23). This approach is based on the ‘Multi-Dimensional Quasi-Discrete’ (MDQD) model described in Section 2. This model is used in our analysis.

The full composition of Diesel fuel containing 98 components has been replaced with 12 and 15 quasi-components/components (QC/C) using the MDQD model. The performances of these two approximations are compared to the ones based on the ME (benchmark model), MI and ND models. The 12 QC/C are formed of 4 alkane QC, 2 cycloalkane QC, 1 bicycloalkane QC, 2 alkylbenzene QC, 1 indane/tetraline QC, 1 naphthalene QC and 1 characteristic component of tricycloalkane (see (23) for details), ignoring negligible contributions of other characteristic components (diaromatic and phenanthrene). The 15 QC/C are formed of 4 alkane QC, 3 cycloalkane QC, 1 bicycloalkane QC, 3 alkylbenzene QC, 2 indane/tetraline QC, 1 naphthalene QC and 1 characteristic component of tricycloalkane (see (23) for details), ignoring negligible contributions of other characteristic components (diaromatic and phenanthrene).

The molar fractions of QC/C are described by the matrix X_{nm} (System (2)), where n refers to the number of carbon atoms, and m refers to the groups (e.g. cycloalkanes) or individual components (tricycloalkane, diaromatic and phenanthrene). The maximal number of non-zero components in matrix X_{nm} is 98. The link between the values of m and the groups of components is shown in Table 2.

Table 2 The relation between parameter m and groups of components in Diesel fuel.

m	Component
1	alkanes
2	cycloalkanes
3	bicycloalkanes
4	alkylbenzenes
5	indanes & tetralines
6	naphthalenes
7	tricycloalkane
8	diaromatic
9	phenanthrene

The time evolution of Diesel fuel droplet surface temperatures (T_s) and radii (R_d) is presented in Fig. 7. The plots are presented for 6 cases: the contributions of all components are taken into account using the Effective Thermal Conductivity/Effective Diffusivity (ETC/ED) model (indicated as (ME)); the contributions of all components are taken into account using the Infinite Thermal Conductivity/Infinite Diffusivity (ITC/ID) model (indicated as (MI)); the composition of Diesel fuel is approximated by 15 and 12 QC/C using the MDQD model (indicated as (15) and (12) respectively); and Diesel fuel composition is approximated by n-dodecane using the ITC model (indicated as (ND)).

As can be seen from Fig. 7, the predictions of Diesel fuel droplet evaporation time (t_{evap}) and T_s using the MI model underestimate t_{evap} by about 7% and T_s by up to 9%, compared to the same values predicted by the ME model. Similarly, the ND model underestimates t_{evap} and T_s by about 55% and up to 7%, respectively, compared to the values predicted by the ME model. At the same time, the approximation of Diesel fuel composition (98 components) with 12 QC/C, using the MDQD model, underestimates t_{evap} and T_s by less than 10% and up to 1%, respectively, compared to the values predicted by the ME model. Also, the approximation of Diesel fuel composition with 15 QC/C, using the MDQD model, underestimates t_{evap} and T_s by less than 6% and up to 0.4%, respectively, compared to the values predicted by the ME model. The reduction of the full composition of Diesel fuel (98 components) to 15 QC/C can make a significant contribution to computational efficiency, with a possible reduction in CPU time by 84% compared to the case when the ME model is used (23; 24), when up to 6% error in the accuracy of predicting droplet evaporation time can be tolerated.

Although the results predicted by the MI model indicate a reasonably close agreement with the ones predicted by the ME model for this particular case, this model cannot adequately describe the underlying physics of the processes inside droplets (heat conduction and species diffusion). Hence, it can lead to more noticeable errors under different conditions or for a broader range of case studies (see (23)). This was clearly shown in the case of biodiesel fuel droplets (see Figs. 1–3 and Table 1) in Section 3.

As in the case of biodiesel fuel droplets, the changes in the behaviour of the droplet radii when using different models are related to the fact that at the final stages of droplet evaporation the mass fractions of species with larger numbers of carbon atoms n at the surface of the droplets increase

at the expense of the species with smaller n (cf. Figs. 4–6). This behaviour is attributed to the contribution of the species diffusion within the droplets. Heat conduction and recirculation inside droplets contribute to the time evolution of droplet surface temperature.

5 Gasoline fuel droplets

In this section, the results of the application of the MDQD model (described in Section 2) to the analysis of gasoline fuel droplet heating and evaporation are described. As in (26), the contributions of the two groups of alkanes, n-alkanes (n-paraffin) and iso-alkanes (iso-paraffin), are considered separately, taking into account the differences in their thermodynamic and transport properties.

An analysis similar to the one presented in (26; 36) is performed but under different engine-like conditions. The composition of gasoline fuel (FACE C) and its thermodynamic and transport properties are inferred from (26; 37). As in (26), the undefined species are ignored and the species with the same chemical formulae and very close thermodynamic and transport properties are merged to form representative components. This has led to the reduction of the original 83 components (see (37)), to 20 components. As in the case of Diesel fuel (see Section 4), the components with similar molecular structures formed separate groups as shown in Table 3.

Table 3 The relation between parameter m and groups of gasoline fuel.

m	Component
1	n – alkanes
2	iso – alkanes
3	aromatics
4	indanes /naphthalenes
5	cycloalkanes
6	olefins

The plots of the droplet surface temperatures (T_s) and radii (R_d) versus time, using four approaches to modelling gasoline fuel droplet heating and evaporation, are presented in Fig. 8.

As can be seen from Fig. 8, the predictions of gasoline fuel droplet evaporation time (t_{evap}) and T_s using the MI model underestimate the values of t_{evap} and T_s by about 5% and up to 4%, respectively, compared to the values predicted by the ME model. The prediction of the IO model underestimates t_{evap} and T_s by about 40% and up to 7%, respectively, compared to the values predicted by the ME model. At the same time, the approximation of 20 components of gasoline fuel with 6 QC/C using the MDQD model underestimates t_{evap} and T_s by only about 2% and up to 0.6%, respectively, compared to the values predicted by the ME model. These trends are similar to the ones presented in Section 4 for Diesel fuel droplets and in (26) for the same fuel but with different input parameters. As in the case of biodiesel and Diesel fuels, the differences in the predictions of different models are attributed to the fact that the mass fractions of heavier (less volatile) components increase at the expense of lighter (more volatile) components near the end of droplet evaporation.

The reduction of the full composition of gasoline fuel (20 components) to 6 QC/C can make a significant contribution to computational efficiency, with up to 70% reduction in CPU time (see (26) for details), when up to 2% error in the accuracy of predicted droplet evaporation time can be accepted.

6 Conclusion

The modelling of heating and evaporation of three types of automotive-fuel droplets has been considered; these are biodiesel, Diesel and gasoline. Modelling of biodiesel fuel droplets has been based on the application of the Discrete Component (DC) model. In the cases of Diesel and gasoline fuel droplets, the recently developed Multi-Dimensional Quasi-Discrete (MDQD) model has been found to be suitable for the analysis of fuel droplet heating and evaporation, based on a compromise between accuracy and CPU efficiency.

In agreement with the previous findings, it has been shown that ignoring the effects of species diffusion, temperature gradient and recirculation inside droplets, or assuming that these species can be replaced by a single component, which are common practices when modelling the heating and evaporation of fuel droplets in many engineering applications, can lead to noticeable errors in the predictions of the droplet surface temperatures and evaporation times of all droplets studied. In the case of biodiesel fuel droplets, it is recommended that the Effective Thermal Conductivity/Effective Diffusivity (ETC/ED) model, taking into account diffusion of all species, is used for the analysis of these processes.

It is pointed out that the approximation of the automotive fuels under consideration, assuming that species mix infinitely quickly or do not mix at all, leads to underestimation of droplet evaporation time with errors up to 27%, for biodiesel, 55%, for Diesel, and 40%, for gasoline fuel, which are not acceptable in most engineering applications.

The main problem with the application of the DC model to the analysis of realistic Diesel and gasoline fuel droplet heating and evaporation lies in the fact that it is computationally expensive. It has been shown that the most efficient (from the point of view of accuracy and CPU efficiency) model for analysing Diesel and gasoline fuel droplet heating and evaporation is the recently introduced MDQD model. It has been shown that the approximation of 98 components of Diesel fuel by 15 quasi-components/components leads to under-prediction of the droplet evaporation time by less than 6%. Also, the approximation of 20 components of gasoline fuel by 6 quasi-components/components leads to under-prediction of the droplet evaporation time by about 2%. These errors are believed to be acceptable in most engineering applications.

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Figure captions

Fig. 1 The plots of time evolution of droplet surface temperatures (T_s) and radii (R_d) of an SME droplet as predicted by the multi-component ETC/ED model (ME), single-component (SC)/ITC model (SI), and multi-component ITC/ID model (MI). The droplet is assumed to have initial radius $12\ \mu\text{m}$ and is moving at $10\ \text{m/s}$ in still air at temperature and pressure equal to $700\ \text{K}$ and $30\ \text{bar}$ respectively.

Fig. 2 The same as Fig. 1 but for an RME droplet.

Fig. 3 The same as Figs. 1-2, but for a PMK droplet.

Fig. 4 The plots of time evolution of surface mass fractions of C16:0M, C18:1M, C22:1M, C24:1M and C18:3M for an RME droplet under the same conditions as in Figs. 1-3.

Fig. 5 The plots of mass fractions of C16:0M, C18:1M, C22:1M, C24:1M and C18:3M versus normalised distance from the centre of the droplet at three time instants, $0.02\ \text{ms}$, $1\ \text{ms}$ and $1.5\ \text{ms}$, for an RME droplet under the same conditions as in Figs. 1-4.

Fig. 6 The plots of temperature versus normalised distance from the centre of the droplet at four time instants, $0.02\ \text{ms}$, $0.5\ \text{ms}$, $1\ \text{ms}$ and $1.5\ \text{ms}$, for an RME droplet under the same conditions as in Figs. 1-5.

Fig. 7 The plots of time evolution of droplet surface temperatures (T_s) and radii (R_d) of a Diesel fuel droplet as predicted by five approaches: the contributions of all components are taken into account using the ETC/ED model (indicated as (ME)); the contributions of all components are taken into account using the ITC/ID model (indicated as (MI)); Diesel composition is replaced by n-dodecane using the ITC model (indicated as (ND)); the composition of Diesel fuel is approximated by 15 and 12 QC/C using the MDQD model (indicated as (15) and (12) respectively), under the same conditions as in Figs. 1-6.

Fig. 8 The plots of time evolution of droplet surface temperatures (T_s) and radii (R_d) of a gasoline fuel droplet as predicted by four approaches: the contributions of all components are taken into account using the ETC/ED model (indicated as (ME)); the contributions of all components are taken into account using the ITC/ID model (indicated as (MI)); the composition of gasoline fuel is replaced with iso-octane using the ITC model (indicated as (IO)); the composition of gasoline fuel is approximated by 6 QC/C using the MDQD model (indicated as (6)). Gas temperature and pressure are assumed equal to $550\ \text{K}$ and $10\ \text{bar}$ respectively.

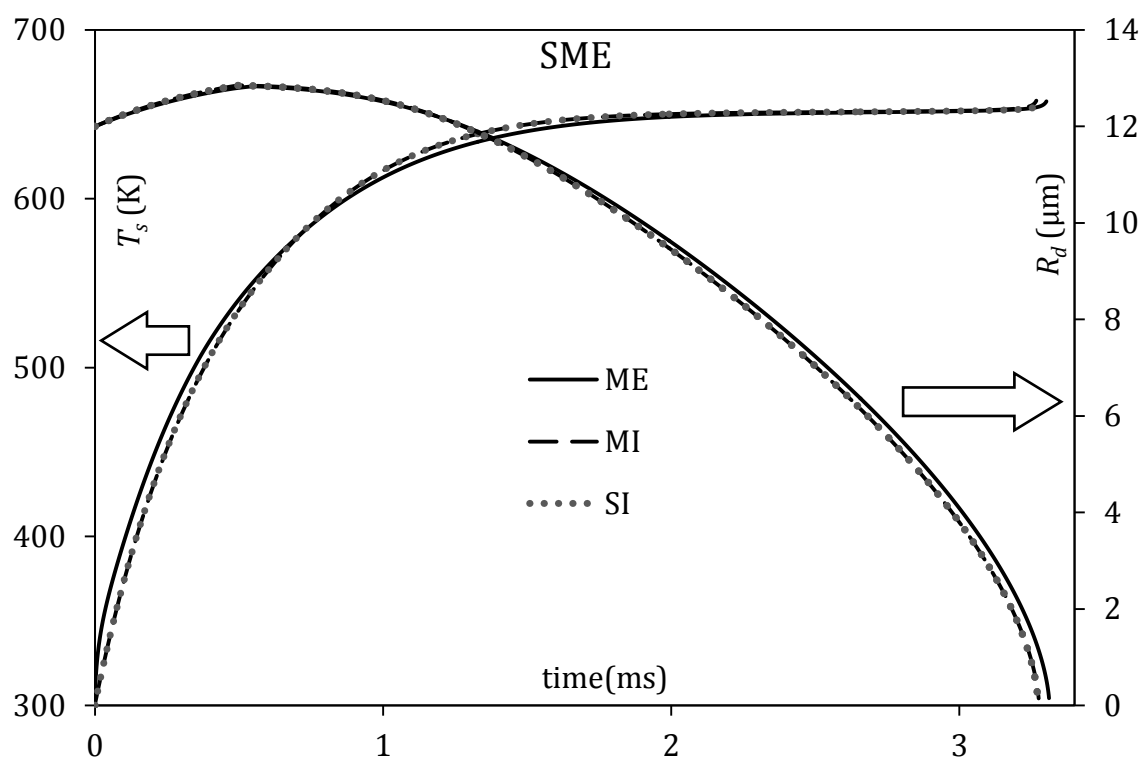


Fig. 1

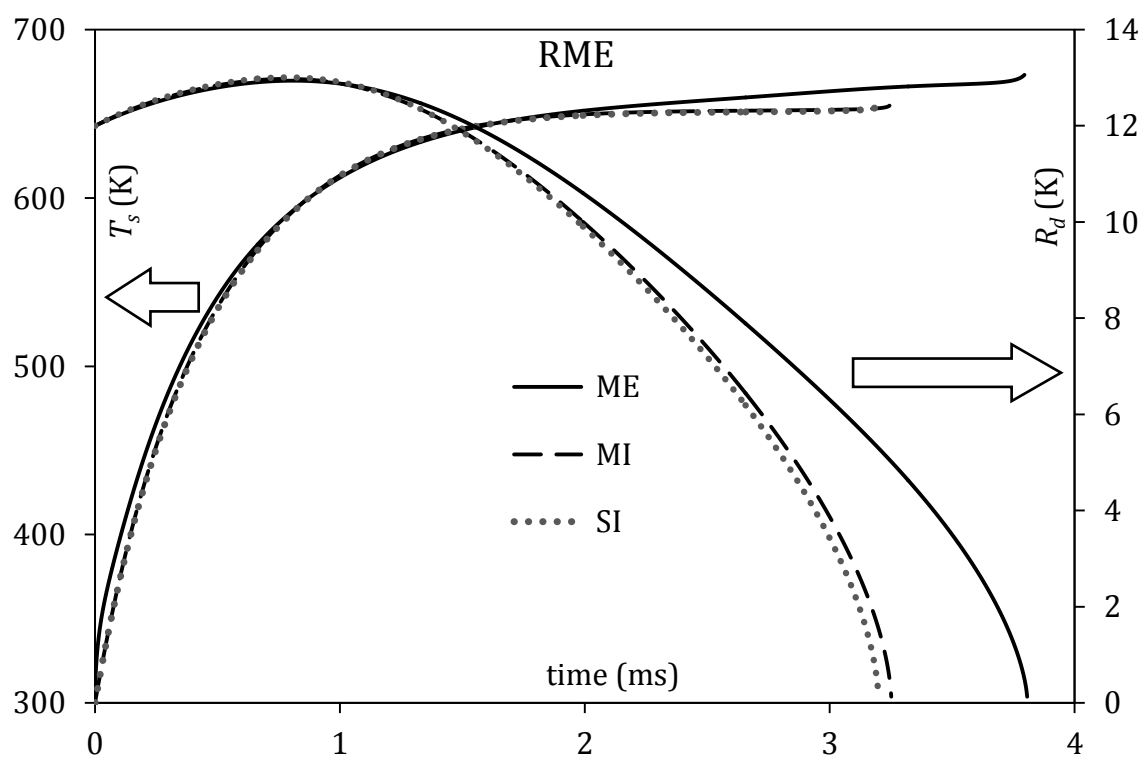


Fig. 2

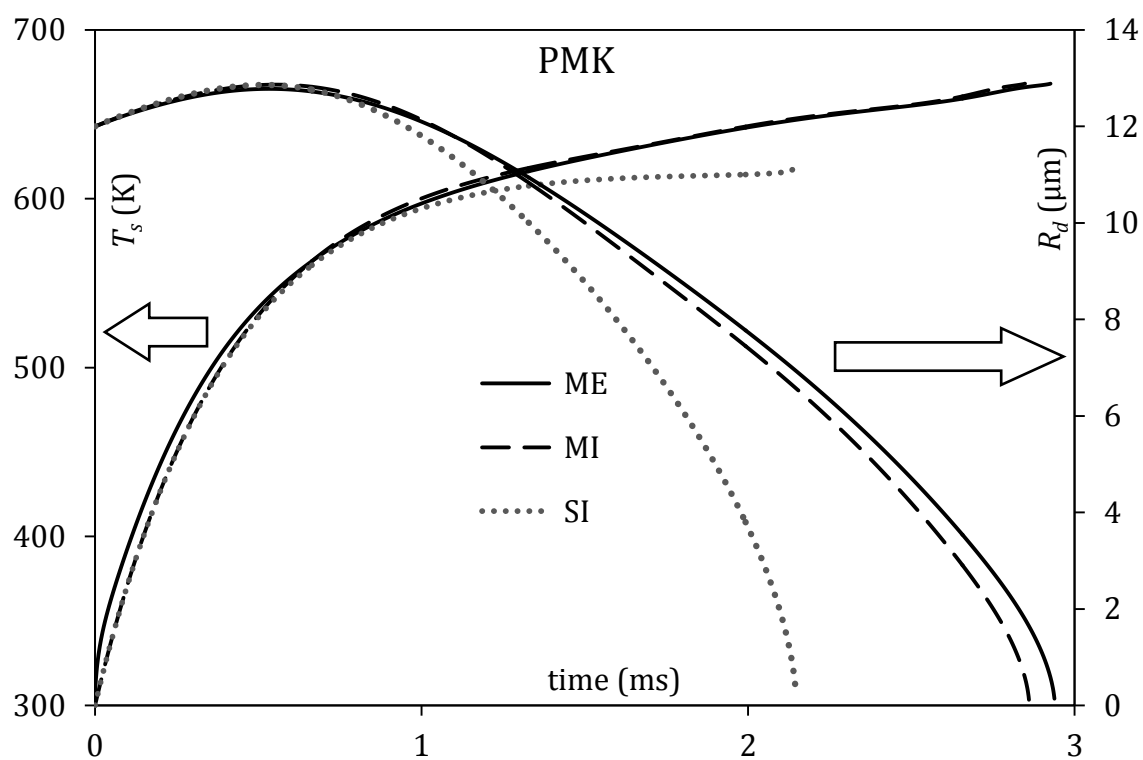


Fig. 3

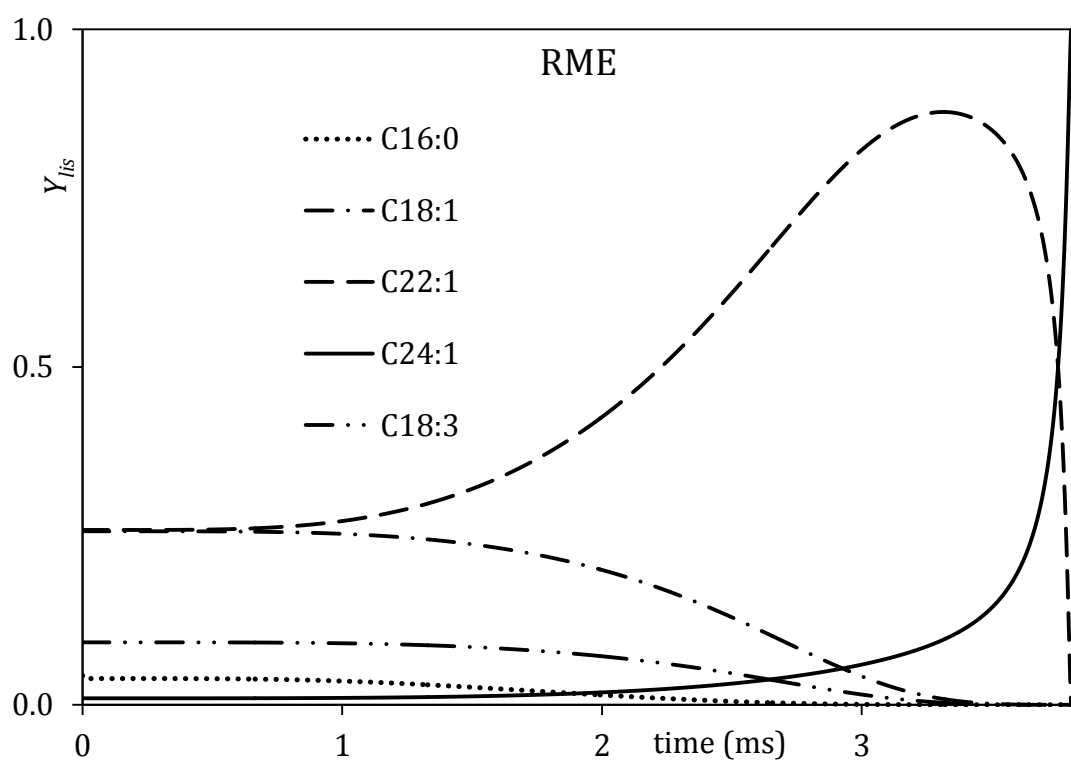


Fig. 4

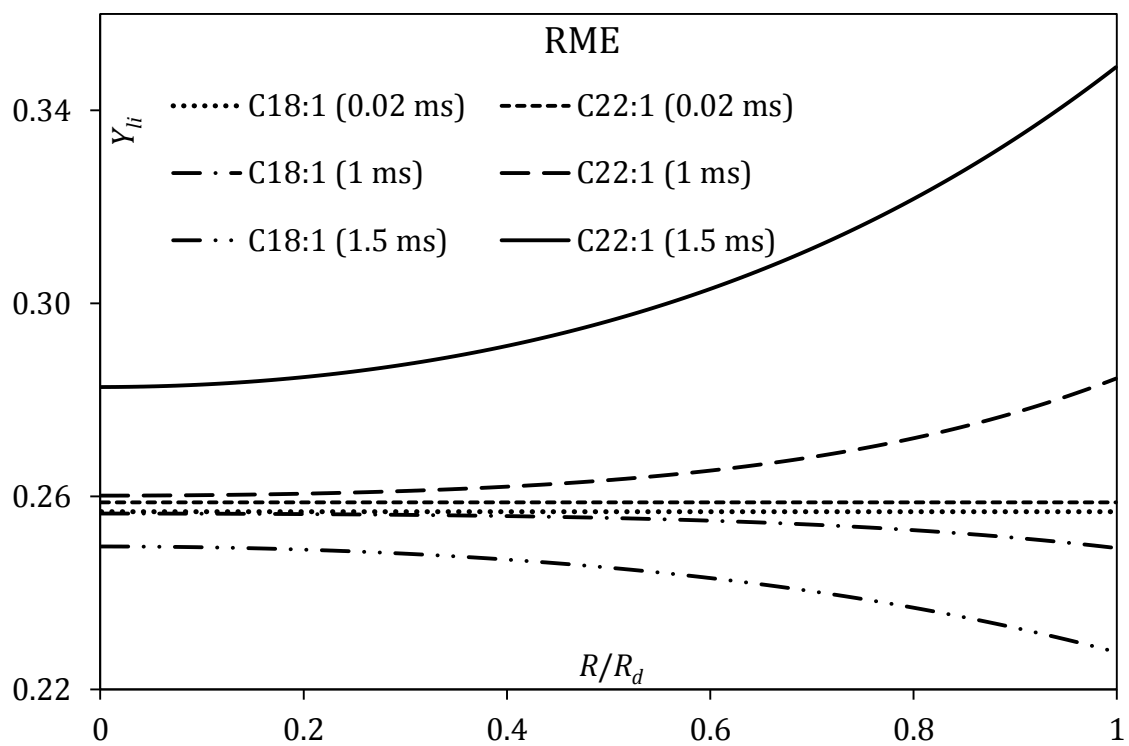


Fig. 5

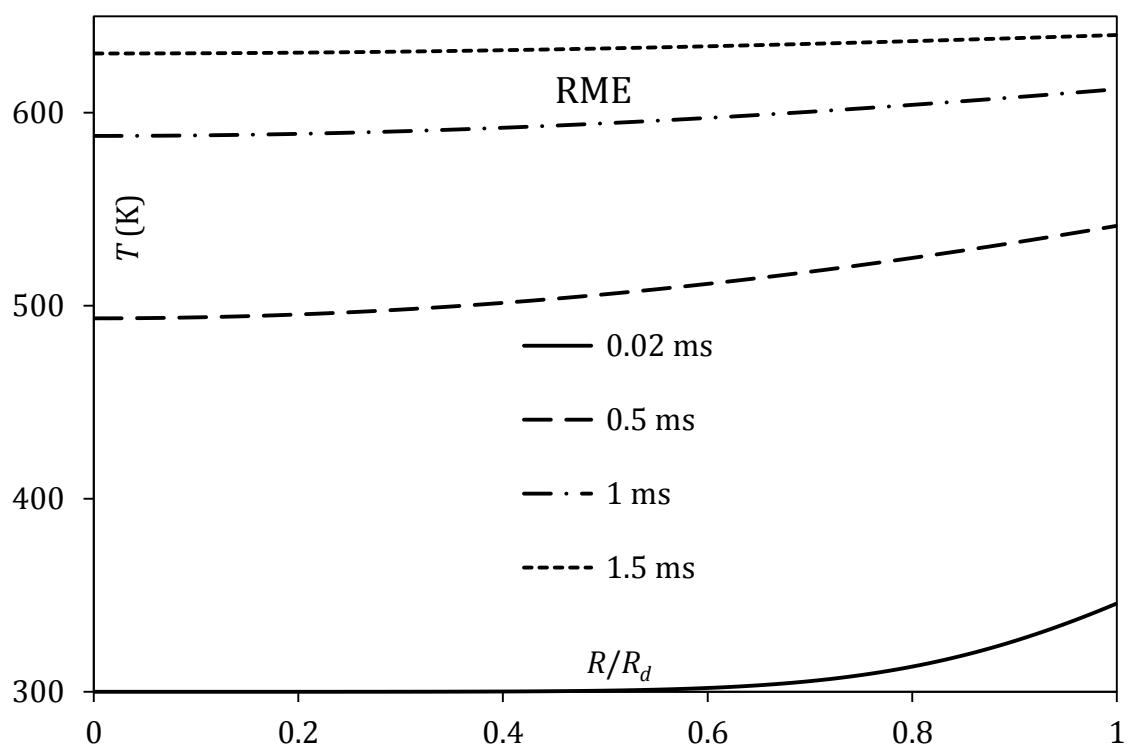


Fig. 6

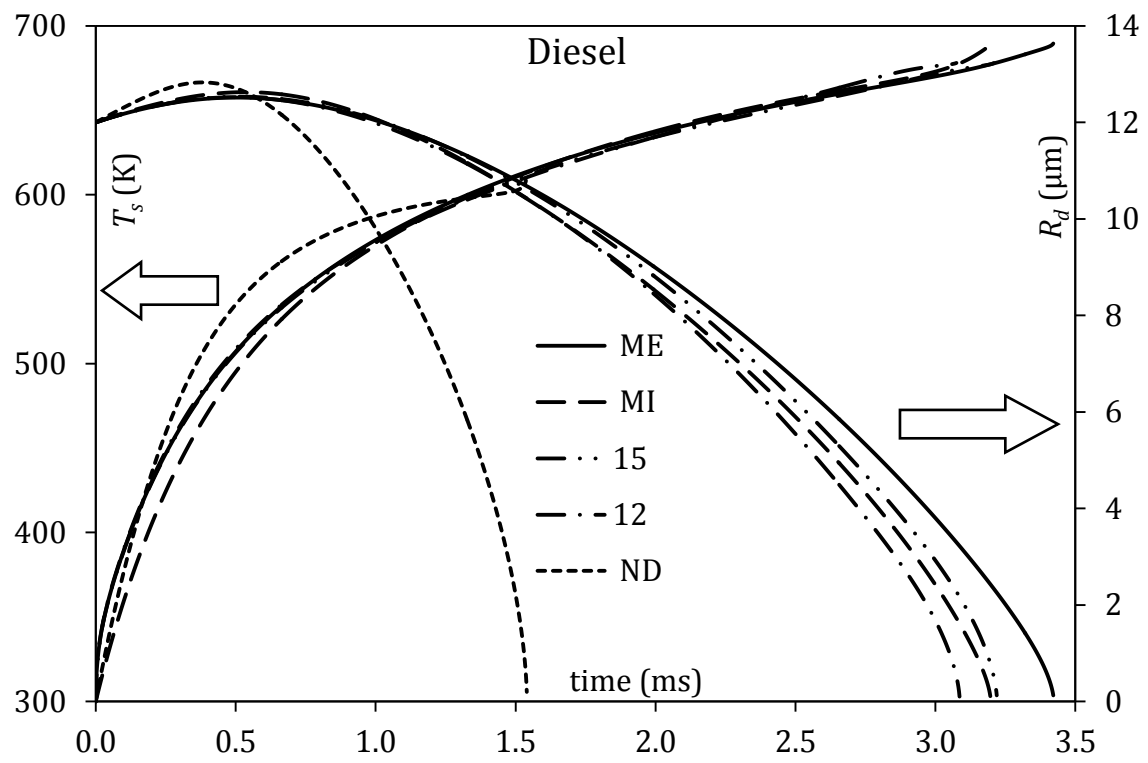


Fig. 7

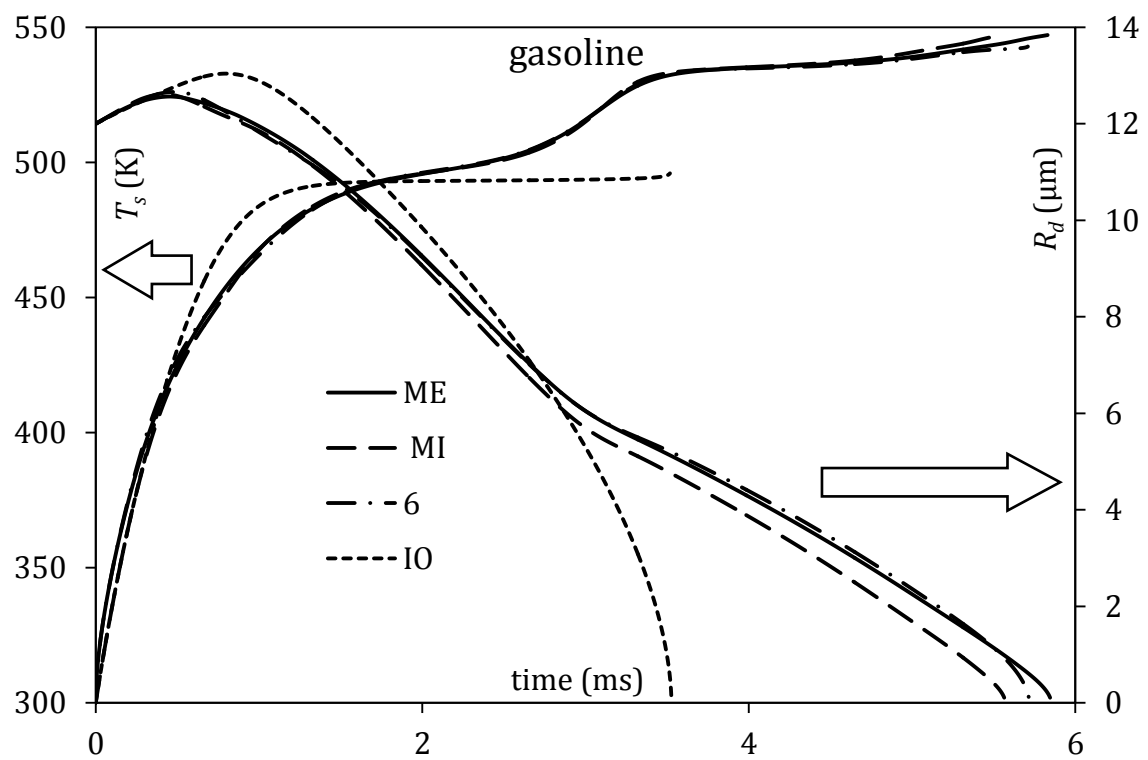


Fig. 8